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Published in:
Scandinavian Economic History Review

DOI:
10.1080/03585522.2018.1503968

Scandinavian Economic History Review

ISSN: 0358-5522 (Print) 1750-2837 (Online) Journal homepage: https://www.tandfonline.com/loi/sehr20

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To cite this article: Cristián Ducoing, Ben Gales, Rick Hölsgens & María del Mar Rubio-Varas (2019) Energy and machines. Energy capital ratios in Europe and Latin America. 1875–1970, Scandinavian Economic History Review, 67:1, 31-46, DOI: 10.1080/03585522.2018.1503968

To link to this article: https://doi.org/10.1080/03585522.2018.1503968

SCANDINAVIAN ECONOMIC HISTORY REVIEW
2019, VOL. 67, NO. 1, 31–46
https://doi.org/10.1080/03585522.2018.1503968

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Energy and machines. Energy capital ratios in Europe and Latin America. 1875–1970

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ABSTRACT
The relationship between energy and capital is one of the most important aspects of modern economic growth. Machines need energy to produce all the goods we enjoy; energy would be far less useful for humankind in absence of machines. However, the great majority of the economic models do not take into account the elasticities of substitution (or complementaries) between these two main variables. Actually, energy is absent in many growth models and discussions on diverging economic development paths. We approach this relevant issue from a new perspective: energy and capital relations during 100 years. We use the latest estimations of capital stock (machinery and equipment) and energy consumption for Latin America and compare them with those of Western Europe. The energy–capital ratio (how much energy is used per unit of capital) could be a predictor of economic growth, thus providing stylised facts about the timing and causes of the different modernisation patterns of these regions and showing us some answers on the long-run relationship between energy consumption and capital accumulation.

ARTICLE HISTORY
Received 1 June 2017
Accepted 27 June 2018

KEYWORDS
Capital stock; energy; energy efficiency; Latin America; Europe

JEL Classification
N70; N10; O33; Q43

1. Introduction

Economic growth models, building on Abramovitz (1956) and Solow (1956), tend to stress the importance of human and physical capital accumulation (Leimbach, Kriegler, Roming, & Schwanitz, 2017; Mankiw, Romer, & Weil, 1992). While there are limits to what extent labour can grow, capital-deepening (i.e. increasing capital per worker) makes enhanced growth possible. Energy is a crucial input for both labour and capital. Both labour and capital can convert energy into useful work.

> But the ceiling for the energy employed directly by labour is the food that can be consumed by each worker. Capital has no such ceiling, or only that imposed by current technology. Thus, in the nineteenth century, capital-deepening production tended to mean energy-deepening production too. (Kander, Malanima, & Warde, 2013, p. 220)

With initial industrialisation, energy-deepening (especially of modern energy carriers) is to be expected, however as argued by Kander et al. (2013, pp. 219–221) and Allen (2012), capital-deepening was the most important driver for increasing outputs.[1] In this paper, we focus on the interrelation

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[1]Following the definition in Gales et al. (2007), we define as traditional energy carriers firewood, food for the population and fodder for draught animals, direct working water, wind and peat and as modern energy carriers coal, oil, natural gas and primary electricity (hydroelectricity and nuclear).

Table 1. GDP per capita (in $GK 1990) in several years.

	1875	1913	1929	1950	1970
Belgium	2.861	4.220	5.054	5.462	10.611
France	1.876	3.485	4.710	5.186	11.410
Germany	1.839	3.648	4.051	3.881	10.839
Italy	1.542	2.564	3.093	3.502	9.719
Netherlands	2.755	4.049	5.689	5.996	11.967
Portugal	975	1.250	1.610	2.086	5.473
Spain	1.207	2.056	2.739	2.189	6.319
Sweden	1.345	3.073	4.145	6.769	13.011
UK	3.190	4.921	5.503	6.939	10.767
Argentina	1.417	4.038	4.610	5.276	7.730
Brazil	691	694	968	1.559	2.871
Chile	1.233	2.836	3.279	3.741	5.120
Mexico	623	1.528	1.602	2.308	4.382
Uruguay	1.833	2.694	4.273	4.873	5.124

Source: Bolt & Van Zanden, (2014) for Europe and Bértola and Ocampo (2012) for Latin America

between energy and capital and examine the divergent histories of Western Europe and Latin America. We cover the period 1875–1970 and argue, supporting our ideas in recent energy history research by Csereklyei, Rubio-Varas, and Stern (2016) and Kander et al. (2013), that the rapid decrease in energy–capital ratios in Europe both growth rates and levels, as compared with Latin America, can help to understand their economic divergence.

Latin American countries began their independence with vast endowments of land and natural resources, and were for a while, more prosperous than some European nations. Nevertheless, over the course of the nineteenth and twentieth century, Latin America did not manage to maintain its position and a divergence between Europe and Latin America emerged (Bértola & Ocampo, 2012). Measures of GDP per capita have shown the increasing divergence in output per capita between Latin America and Western Europe (see Table 1).

There have been several studies to measure and explain these differences[2] Both physical capital stocks (Tafunell & Ducoing, 2016) and energy consumption (Rubio, Yáñez, Folchi, & Carreras, 2010; Yáñez, Rubio, Jofré, & Carreras, 2013) have been used as proxies for economic development, and as explanations for the divergence. In this article, we look at the ratio between energy and capital. We observe noticeable differences among the countries. By-and-large, we see a rapid decrease in energy–capital ratios in most (Western) European countries in the twentieth century. For Latin America, the findings are more complex: Mexico resembles the European countries, albeit with some delay, for the other Latin American countries no clear downward trends can be discerned in the twentieth century. We tentatively argue that this may help to explain differences in economic development, as a declining energy–capital ratio signals technological advancement and efficiency increase (i.e. less energy is required to produce economic output). Above all, we claim that catch-up by developing countries without improvements in energy efficiency is worrisome. The paper iso-rganised as follows. In Section 2, we explain the theory behind the relation between energy and capital; in Section 3, the data used in this research are made explicit; Section 4 presents the results of the comparison and Section 5 concludes.

2. Energy–capital ratios as indicator of economic development

The modern energy/capital stock in machinery ratio (hereafter, Em/Km&*e* ratio) as an indicator of economic development, it is important to first address the roles of both energy consumption and capital accumulation separately. The relationship between energy and economic development is complex. Csereklyei et al. (2016) find, not surprisingly, that energy use per capita increased over

[2]See, for example, Bulmer-Thomas (2003) and Maddison (2007).

time as incomes grew; even though there might be some 'decoupling' in developed countries in recent years and the energy intensity (E/GDP) of European countries declined over the last two centuries (when traditional energy sources are included) (Gales, Kander, Malanima, & Rubio, 2007; Kander et al., 2013). The Industrial Revolution is often linked with the increasing usage of energy (in particular coal), but whether coal consumption sparked the Industrial Revolution, or whether it was mainly a consequence of economic development is still subject of debate (Allen, 2009, Chapter 1; McCloskey, 2010, Chapter 22). Moreover, the question of causality between energy consumption and economic development is still contested (Liddle & Lung, 2015; Payne, 2010). According to Kander et al. (2013)

> energy consumption, and the availability of coal, helped propel economic growth (as did other things). Consumption of coal seems to have been a key part of economic success (…) and cheap energy was a necessary condition of the industrial revolution. (p. 209)

They argue nevertheless that capital-deepening was the most important driver for increasing outputs.

In a Cobb-Douglas production function where output is a function of labour and capital, there are limits to the extent in which labour can grow, capital-deepening makes enhanced growth possible. De Long and Summers (1991), for instance, have argued that there is a strong causal relationship between investments in equipment and economic growth[3] However, for machinery and equipment to produce output and economic growth, input of energy is required.

Nonetheless, over the long run, the ratio between capital stock and energy consumption changed notably. Kander et al. (2013, p. 338) present trends for Sweden, Spain and Britain and conclude that in all three of these countries the energy to capital ratio decreased notably[4] The extent to which this ratio changed is not the same in all countries and depends a lot on the initial levels of both capital stock and energy consumption, but an overall trend towards relatively less energy input per unit of capital is clear. As the energy capital ratio informs us about the amount of energy needed per unit of capital, a decreasing trend signals energy efficiency improvements.

Energy is a crucial input for economic growth through its direct relationship with the productivity of both labour and machinery; without energy no production hence no economic development. However, thermal efficiency of machinery and equipment has increased over the years (Ayres & Warr, 2009) and also the economic efficiency of energy conversion has increased (at least in the West) (Gales et al., 2007; Kander et al., 2013). This means relatively, less energy is needed to produce the same output. Kander et al. (2013, Appendix A) present a growth accounting model which incorporates energy.[5] They show how energy quantity, quality and augmentation (i.e. energy saving biased technological change) contribute to economic growth. Stern and Kander (2012) find that especially during the Industrial Revolution expansion of energy services was a major factor in explaining economic growth (for the case of Sweden), but later capital and labour-augmenting technological change becomes the dominant factor.

In other words, when energy is scarce it can be a constraint on economic growth (i.e. the pre-IR 'Malthusian' steady state), but once energy is relatively abundant (i.e. make up a smaller cost-share) capital becomes increasingly more important (Stern & Kander, 2012). This, it could be argued, is in line with the at first sight, controversial finding of Bretschger (2015) that increasing energy prices are beneficial to economic growth. Bretschger argues, based on a data set which starts in 1975, that increasing energy prices spur innovation, and that these additional investments foster long-run economic growth. With the emergence of industrialisation, the consumption of (modern) energy

[3].In their 1993 extension of the 1991 paper, they confirm this relationship especially for developing countries (De Long & Summers, 1993). In this same line, is worth to mention the article by Delong (1992), about the relationship between equipment investment and productivity in the long run.

[4]Notice that Kander et al. speak of the capital to energy ratio (K/E), hence they speak of increases in the K/E ratio, rather than its reverse.

[5]Based on Stern and Kander (2012).

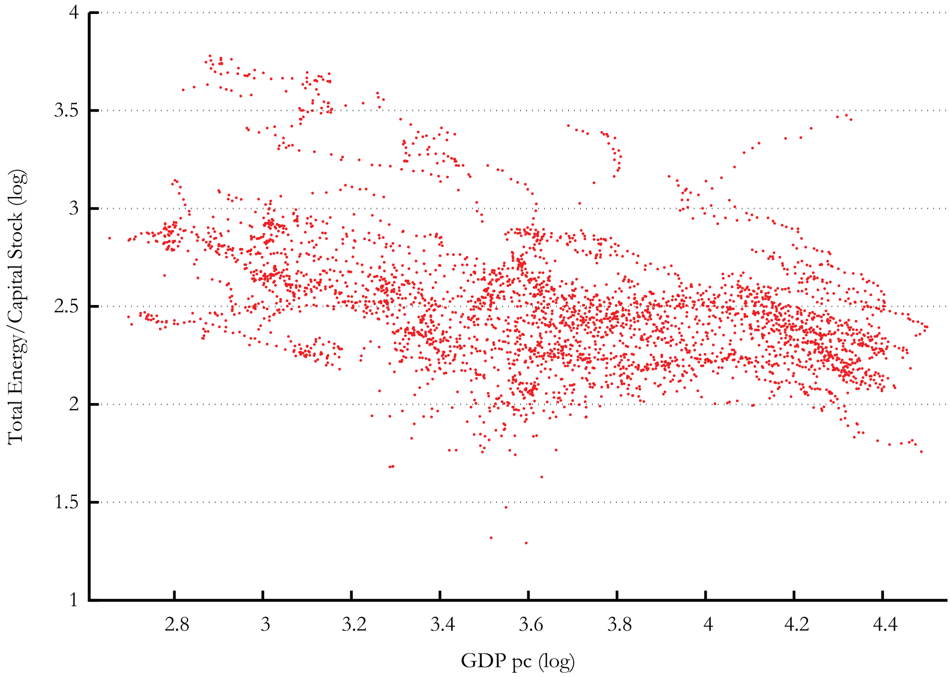

Figure 1. Energy/capital vs. GDP per capita. 99 countries over the period 1971–2010. Sources: Capital Stock Groningen Growth and Development Center. FebPwt – penn world table – international comparisons of production, income and prices (8.0); GDP per capita The Maddison-Project, Maddison update 2013. Accessed May 19th and Energy Consumption (Csereklyei et al., 2016).

sources may be expected to rise, but investments in new, modern, more energy-efficient machinery and equipment will be crucial for long-term economic development. As the energy–capital ratio captures the consumption of energy relative to the accumulation of capital a decreasing energy–capital ratio signals economic progress through investment in higher quality capital. This claim finds support in existing data for the more recent period: countries with lower energy–capital ratios tend to be richer than countries with a high energy–capital ratio (see Figure 1).

This graph does not show trends over time, but it does suggest a correlation between the energy–capital ratio of a country and its economic performance: lower E/K ratios by and large correspond with higher per capita income (the observations in the top-right of the graph mainly correspond with oil producers). Csereklyei et al. (2016) cover the period 1971–2010 and find that, at least for rich countries, E/K ratios declined, in line with the findings by Kander et al. (2013). Interestingly though, they found increasing E/K ratios in 'many developing countries, particularly in Africa and in Latin America' (Csereklyei et al., 2016).

As we believe decreasing E/K ratios signal economic development through efficiency increases, the reversed trends for these developing countries may be reason for concern. Increasing E/K (at the periphery) in combination with decreasing E/K (at the core) is worrisome. Worrisome in the light of a production function view with technology as universal blue print. For an increase in E/K might signal development, but not development with the best technique. Furthermore, increasing energy–capital ratios in developing regions is also a reason for environmental concern. If these developing regions (Latin America, but also other regions not included in the current study, such as South-East Asia and China) realise catch-up growth only based on capital-deepening without improving their energy efficiency, their economic development will be unnecessarily energy intensive and thus emission-intensive. Figure 2 also opens up the question: Is this divergence between, in our case, Europe and Latin America a structural, long-term, phenomena? In order to figure out a compelling answer, we only focus on the period up to 1970, because as Kander et al. (2013) stress, the emergence of less

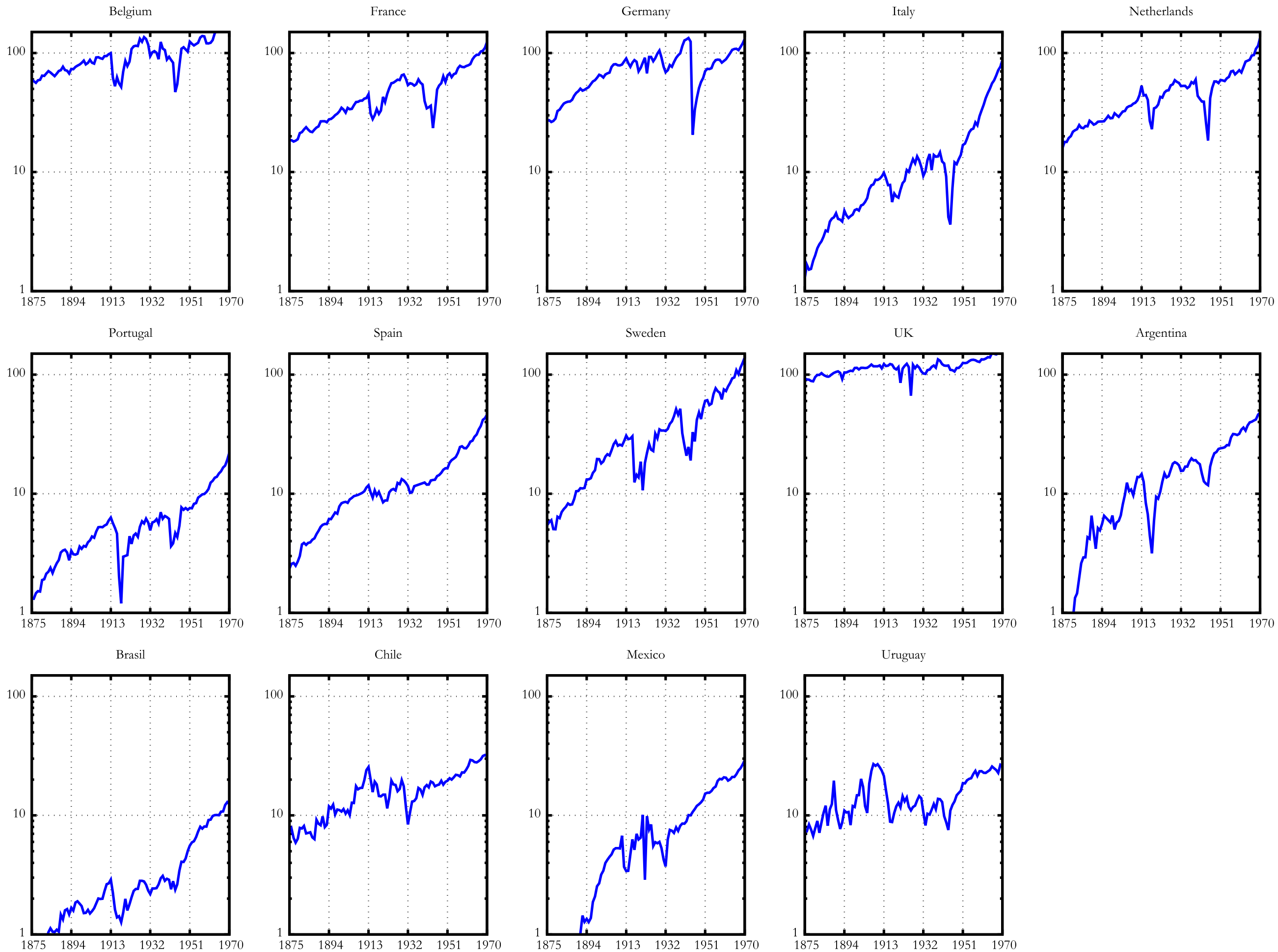

Figure 2. Energy consumption in modern energy carriers. Peta Joules. Several countries, 1875–1970.

energy-intensive information and communication technologies (since the 1970s) caused a break in the trends towards quicker decreases in the European countries they compared.[6]

3. Data

The E/K ratio we have been discussing so far (in the theory and empirical findings of Kander et al. (2013), Kander and Schön (2007) and Csereklyei et al. (2016)) applies to all energy consumption (modern and traditional) and to the entire fixed capital stock (i.e. capital in machinery & equipment, infrastructure and residential and non-residential constructions). Because of data limitations, it is impossible to extent both time series back into the nineteenth century though. We therefore have to work with data on the consumption of modern energy carriers, and capital in machinery and equipment only. This has a number of important implications, as we will show below with the example of the Netherlands (a country for which we have all data for a long period), but before discussing these, we first introduce the data sources we use. Beyond the data limitations, the use of modern energy carrier is intrinsically linked with the existence of machinery and equipment to produce and transport goods.

3.1. Energy data

Data availability, especially from the side of the Latin American countries, compel us to restrict our analysis to the use of modern energy carriers (i.e. fossils and modern renewable such as hydroelectricity). An obvious downside of this restriction is that, especially in the nineteenth century, traditional organic energy sources still made up substantial shares of the total energy consumption for many of our sample countries. The first consequence of this limitation is that the total energy consumption of a country will be underestimated and the further we go back in time, the more this will be the case. Since the share of modern energy sources in the total energy mix increases over the time, the second consequence is that the growth of energy consumption may appear larger than it actually was. Gales et al. (2007) have shown the importance of including traditional sources of energy to get a proper view on the historical trajectory of energy intensity. When only modern energy sources are included, the energy intensity of European countries shows an inverted U-shape, when also traditional energy sources are included, most countries show constantly decreasing energy intensities[7] As the example of the Netherlands will also make clear, when a country is in transition from traditional to modern energy sources, it may appear as if the energy consumption of the country is increasing rapidly, while in fact the increase is more gradual because of the substitution of modern energy carriers for traditional sources.

We sampled our energy consumption data from a number of sources. Firstly, we take the data on energy consumption in Latin America from Rubio et al. (2010) and Yáñez et al. (2013). For a number of European countries, country-specific energy consumption series have been published: Italy (Malanima, 2006), Netherlands (Gales et al., 2007), Portugal (Henriques, 2011) Spain (Rubio, 2005)[8], Sweden (Kander, 2002) and the UK (Warde, 2007); for the additional European countries (Belgium, France and Germany) we use unpublished data collected by Ben Gales (see Table 2).

Figure 2 presents the consumption of modern energy (i.e. fossil fuels, hydroelectricity, nuclear energy and modern renewables) in the respective countries per capita. Both total energy consumption as well as energy consumption per capita grew for all countries up until the energy crises of the 1970s. With the exception of Spain and Portugal, the European countries overall used many times more energy per capita than the Latin American countries in our sample. Chile and Uruguay stand out as Latin American countries with relatively high energy consumption per capita in the late

[6]Warr and Ayres (2012) found that, before the rise of ICT, exergy can largely explain the Solow-residual . After the 1970s exergy is no longer the sole explanation for TFP, the ICT-revolution turned information in a major factor increasing total factor productivity.
[7]See also Kander et al. (2013, Figures 10.11 & 10.12); the only noteworthy exceptions are the UK and Germany at the height of their industrialisation.
[8]We use the most recent and revised data (Gales et al., 2007).

Table 2. Energy consumption (in TJ) per 1000 inhabitants.

	1875[a]	1913	1929	1950	1970
Belgium	59.88	99.76	135.94	102.71	189.1
France	18.59	45.04	65.10	57.07	123.9
Germany	27.12	90.11	105.07	61.83	131.5
Italy	1.29	9.87	13.55	13.96	86.9
Netherlands	15.91	53.11	59.17	55.95	134.1
Portugal	1.32	6.32	5.64	7.33	22.1
Spain	2.35	25.13	27.01	26.63	46.2
Sweden	5.43	30.73	34.74	52.38	139.2
UK	92.70	122.84	119.11	118.40	160.0
Argentina	0.69	14.64	18.40	23.79	48.1
Brazil	0.96	2.89	2.79	5.02	12.5
Chile	7.30	25.53	19.80	19.17	31.4
Mexico	0.06	3.41	5.99	13.60	29.1
Uruguay	7.37	21.42	13.39	16.13	26.1

[a]Source: Energy (Gales et al., 2007; Rubio et al., 2010) and population (Bértola & Ocampo, 2012; Bolt & Van Zanden, 2014).

nineteenth century; however, whereas the energy consumption in most countries increased throughout the twentieth century, energy consumption per capita stagnated in these countries in the mid-twentieth century.[9]

3.2. Capital stock in machinery and equipment

Several scholars have done research on capital stock formation to provide estimates for Europe (e.g. Maddison, 1994). For Latin America, the main research has been elaborated by Hofman (2000) and Tafunell and Ducoing (2016). For data on capital stock, we run into comparable data limitations we also faced for energy. Also here, especially the Latin American data compel us to restrict ourselves to one part of the capital stock: machinery and equipment. This also has some serious implications for our analysis. First of all, the heating (or potentially cooling) of buildings requires energy as well which we cannot take into account in the current analysis. Second, machinery tends to increase more than other capital (Kander et al., 2013, p. 30). This means that, when dividing energy consumption by capital in machinery and equipment, the changes over time will be more pronounced than the findings of Kander et al., who divided energy consumption by total capital stock.

The study of the capital stock in the developed world has been a recurrent research topic. The seminal works of Goldsmith (1951), Kuznets (1961) and Feinstein (1972, p. 8) have provided a reference for subsequent studies conducted on many industrialised countries. The most common way to estimate the capital stock is the Perpetual Inventory Method (PIM) which consists of the weighted sum of past investment flows. The gross stock is calculated by adding the cumulative year-to-assets and subtracting totally worn (withdrawals).

To calculate the gross stock in year t, we follow Feinstein (1988).

(1) $GFCS_{t-1} + GFCF_t - Rtr = GFCS_t$

Where $GFCS_{t-1}$ is the stock of year $t-1$, $GFCF_t$ is fixed capital formation in the current year (t) and Rtr are capital withdrawals produced in the current year. The net stock is obtained by subtracting the gross stock depreciation, which is expressed in mathematical terms as follows:

(2) $NFCS_{t-1} + GFCF_t - \delta - \delta(Rtr) = NFCS_t$

[9]The UK shows a similar trend in per capita consumption, as Britain was the workshop of the world in the late nineteenth century, this is less remarkable.

Table 3. Capital stock in machinery & equipment per 1000 inhabitants.

	1875	1913	1929	1950	1970
Belgium		2144[a]	2328	2883	6036
Germany	739[b]	1063	1028	1222	5335
Italy	391	1306	702	1757	5643
Netherlands	611	1685	2416	2216	7742
Portugal		24	43	161	779
Spain	214[c]	356	650	682	3052
Sweden	215	751	1188	4.309	12311
UK	403	858	1416	2.132	5642
Argentina	19	364	371	639	1614
Brazil	96	681	602	571	747
Chile	61	504	626	479	725
Mexico	13	180	237	553	1948
Uruguay	356[d]	1044	1073	2245	2293

[a]Data for 1914.[b]Data for 1935.[c]Data for 1890.[d]Data for 1884.

Where $NFCS_{t-1}$ is the net capital stock at the beginning of year t, $GFCF_t$ is the gross fixed capital formation during the year, δ is the depreciation during the period, $\delta(Rtr)$ are depreciated capital goods removed during the year t and $NFCS_t$ is the net capital stock at the end of period t.

The PIM requires two masses of information: historical series of GFCF at constant prices, for each type of asset and the capital stock in the initial year (OECD, 2009). The latter can be derived directly from the first mass of information, when you set the initial year in the terminal year of life of the first generation of assets with the greatest longevity. For example, with respect to the nineteenth century, if we attribute a life of 50 years to non-residential buildings and we have investment series dating back to 1850, the initial year of the aggregate capital stock is 1900. This is precisely the option we have chosen. The initial year of the capital stock in equipment so became 1875, a consequence of the assumption that, the life of these assets was 25 years during this period. Maddison published historical series of productive capital accumulation (non-residential capital) for six developed economies: Germany, France, UK, Japan, USA and the Netherlands (Maddison, 1994). We used data of Germany, France and UK; for the Netherlands new estimates have become available since 1994. We replicated Maddison's methodology for the other the countries. The data sources for the other European countries were the Netherlands (Albers, 1998; Groote, Albers, & De Jong, 1996), Sweden (Schön & Krantz, 2012), Belgium (Van Meerten, 2003), Italy (Toniolo, 2013), Portugal (Gomes da Silva & Lains, 2013) and Spain (Prados de La Escosura & Rosés, 2010). Tafunell and Ducoing (2016) calculated estimates of capital stocks for Argentina, Brazil, Chile and Mexico. There are series available in Tafunell (2009); Tafunell and Ducoing (2016) allowing to expand the estimates to other Latin American countries.[10] We used the same methodology as in Tafunell and Ducoing (2016).

We can observe huge differences in capital stock in machinery & equipment, both within the regions and across them, especially at the end of the period (see Table 3). Up until the 1950s, the Latin American countries, and most notably Uruguay, can keep up with the European countries. Between 1950 and 1973, the European countries increased their capital stock roughly by a factor of 3–5; the only Latin American country that comes close to this is Mexico. However, if we observe the long run, this situation was different before the First World War. Chile, for example, had US$ G-K 504 in machinery per 1000 inhabitants in 1913 and Sweden has just 1.5 times more. If we jump to 1970, this difference has changed to a ratio of 17 (to Sweden).

3.3. Implications of our data choice: the example of the Netherlands

As mentioned above, the usage of modern energy sources rather than total energy consumption and the usage of capital stocks in machinery and equipment rather than total capital stocks has a number

[10]For an analytical description of the long-term evolution of Gross Fix Capital Formation in Latin America, see Tafunell (2013). Series from Uruguay were contrasted with the work done by Román and Willebald (2015).

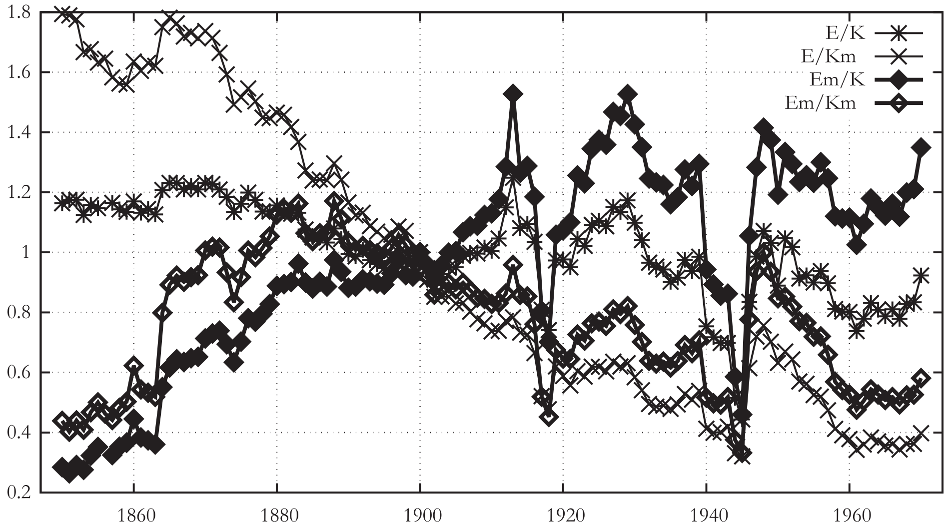

Figure 3. Energy–capital relations in the Netherlands, 1850–1970 (1900=1). Sources: Energy data: (Gales et al., 2007); Capital data: (Albers, 1998) and (Groote et al., 1996).

of consequences that limit the comparability of our analysis with the findings of Kander et al. (2013) and Csereklyei et al. (2016). Therefore, before presenting the results of our analysis, we first work out the case of the Netherlands by way of example. For the Netherlands, we have long-term time series on all relevant variables: modern energy consumption, total energy consumption, total fixed capital stock (K), and capital in machinery and equipment. Even though machinery and equipment were, especially in the earlier stages of industrialisation, the most important aspect of capital-deepening (Kander et al., 2013), it is only a subset of all capital. Other forms of capital require energy as well, for example for heating or cooling of houses and office buildings. Unfortunately, we cannot divide energy consumption among these different forms of capital for lack of disaggregated data. Figure 3 shows what happens when we use modern energy sources only, and what the result is of the use of machinery and equipment rather than total capital stocks.

As Figure 3 shows, if we look at the ratio between total energy consumption and all capital, we see an overall decrease over this period, although it is less pronounced as than findings for Spain, UK and especially Sweden by Kander and Schön (2007). There are two important reasons for this. First of all, the Netherlands started with relatively high levels of capital. Second, the Netherlands transformed into a rather energy-intensive country during the 1960s; therefore, the E/K ratio increases again at the end of our period (after the 1970s it also decreased again).[11] During most of the nineteenth and twentieth century, attempts to economise on fuel were the norm though (Ayres, Ayres, & Warr, 2003). This can also be seen from the ever-decreasing energy intensity levels documented by Gales et al. (2007). They found that according to their new series, 'energy intensity tends to decrease, except during the 1950s and 1960s: a period of fast economic growth and very low energy prices' (Gales et al., 2007, p. 236). However, overall, the decrease is noticeable.

If we, instead, limit the capital stock we take into account to machinery and equipment, the decreasing trend becomes a lot more visible. The main reason for this is that in the mid-nineteenth century, the Netherlands was still relatively non-industrialised, and the accumulation of capital in the form of machinery and equipment went a lot quicker than the accumulation of other forms of capital. By looking only at machinery and equipment, we therefore capture investments in this more productive form of capital, and see more clearly an increase of efficiency. Since we do not know exactly how much of the

[11]The post-Second World War boom in energy consumption was a historical anomaly. During this period, characterised by Pfister with the 1950s syndrome, energy seemed to be available in unprecedented and unlimited supply (Pfister, 2010).

energy was exactly used to power these machines, and how much was used for other purposes (such as heating), this decrease may well exaggerate the efficiency improvements though.

Besides using a subset of all capital, we also use a subset of all energy consumed, namely modern energy only (Em). Let us first see what the effects are of considering only modern energy sources (in this case excluding peat), but all accumulated capital (Em/K). Now, we no longer see a declining trend, but rather a weak U-shape. Since the share of modern energy carriers in the entire energy system increased rapidly in the nineteenth century, this is not surprising. As in the twentieth century, and especially after the Second World War, virtually all energy was derived from modern sources, the E/K ratio and the Em/K ratio are essentially the same (because 1900 is set to 1 the deviations in the Em/K appear somewhat more pronounced, the decreasing path is entered much later because of the substitution of modern energy for traditional sources that was still taking place before the Second World War).

Finally, we arrive at the energy–capital ratio we are using in this paper: modern energy over capital in machinery and equipment (Em/Km&e). Here, we see the increasing trend caused by the transition to modern energy sources in the nineteenth century, but then a decrease during the twentieth century. We see that after the Second World War, energy consumption increased rapidly, while the accumulation of capital in machinery and equipment initially remained slightly behind, but the downward trend is quickly continued until the 1960s when the discovery of domestic natural gast boosted energy consumption.[12]

What does this exercise tell us about the comparability of our indicator with the indicators used by Kander et al. (2013) and Csereklyei et al. (2016)? And what does it mean for the international comparison in the remainder of this paper? Firstly, we have to observe that focusing on machinery and equipment means that we may expect a more pronounced decreasing trend because the accumulation of machinery and equipment speeds up with economic development and goes quicker than the accumulation of other forms of capital (i.e. industrialisation, see Kander et al., 2013). Secondly, the exclusion of traditional energy means though that we might expect an inverted U-shape, especially in countries where the transition to modern energy carriers developed relatively late, and was still going on in the twentieth century. Nonetheless, over the long run, more industrialised/developed countries will still present a decrease in the E/K ratio in the more modern period. We may therefore expect that our findings for Em/Km&e, even though they might exhibit an increase in the earlier period, should show efficiency improvements through eventual decreases.

4. Results

4.1. UK index

We have constructed an index (UK 1890=100) to understand the trends of the several countries of our study. This index allowed to calculate standardised growth rates over the total period and over several sub-periods. Figures 4 and 5 give a graphical representation of the index between 1875 and 1975. One of the interesting results of this exercise, is to appreciate the differences between Europe and Latin America in the long run. We can classify regions. Taking growth over the full period, three groups emerge. The decreasing growth rates group, the stable growth rates group and the increasing growth rates group. The first group comprises Netherlands, Spain, Sweden, UK, Chile and Uruguay; the second group includes Argentina and Germany; and the last one consists of Italy, Mexico and Brazil. These results do change if other periods are chosen. Table 4 specifies several ones. The most dramatic change occurs when the year 1930 is used as starting point.

Figures 4 and 5 and Table 5 show the Em/Km&e ratios for the European and Latin American countries, respectively. We see that the rate of the decline (i.e. the steepness of the curves) may differ substantially; this is related to both the initial levels of capital and the energy intensity

[12]Figure 3 represents the Modern Energy/Machinery & Equipment ratio in a longer period.

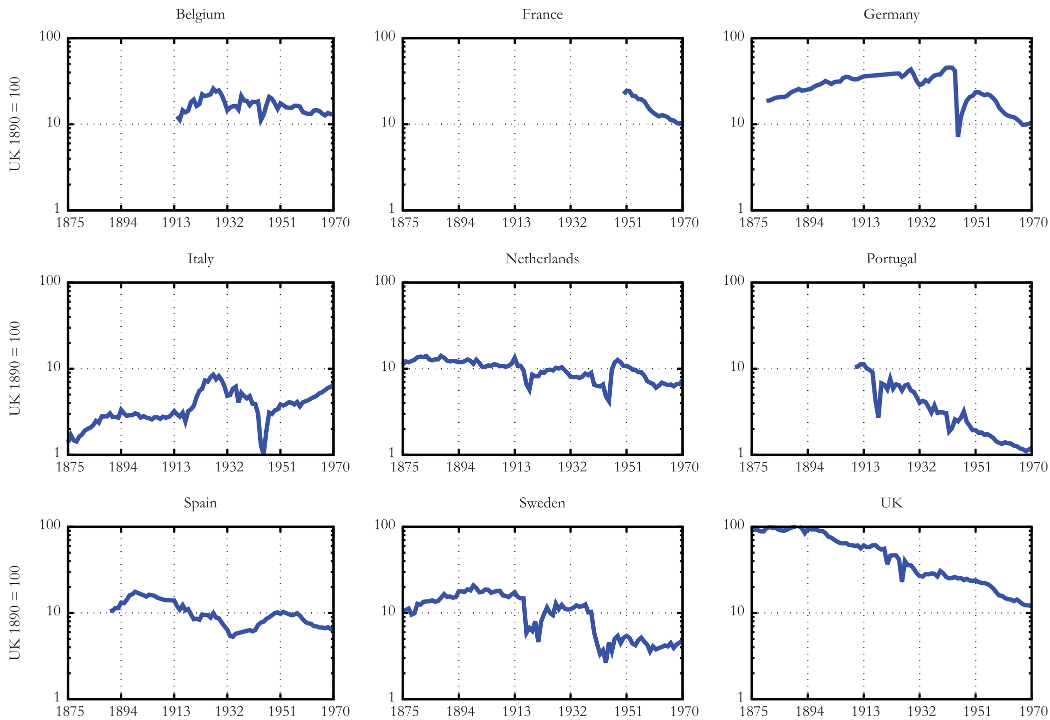

Figure 4. Energy–capital ratios in Europe, 1875–1970 (UK 1890=100).

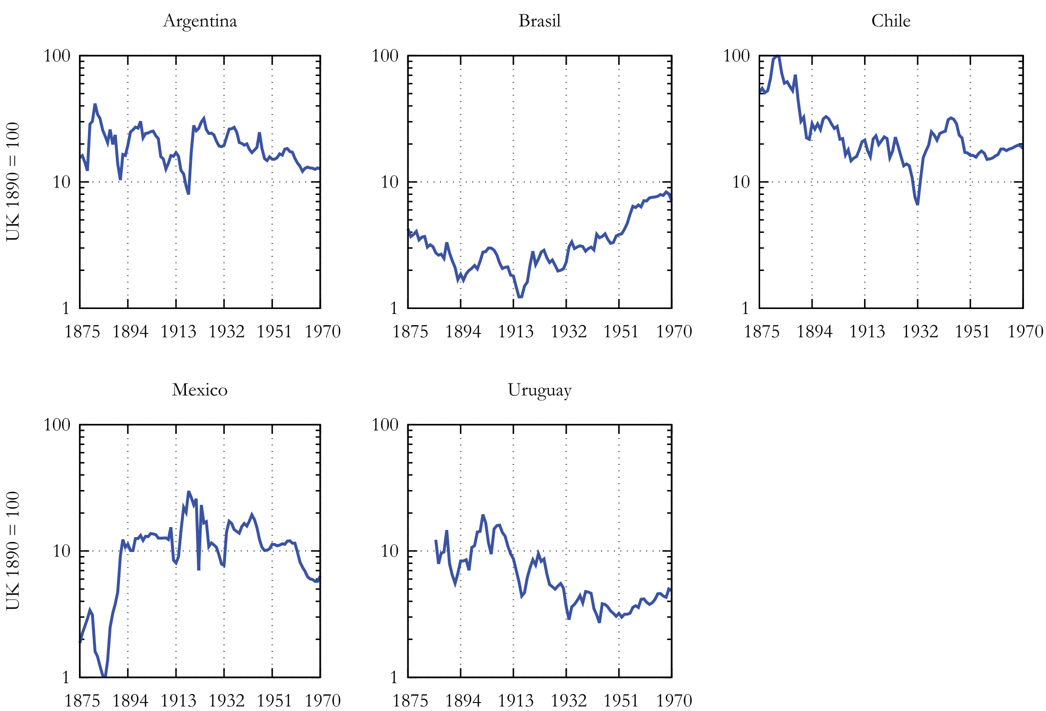

Figure 5. Energy–capital ratios in Latin America, 1875–1970 (UK 1890=100).

Table 4. Growth rates modern energy/capital in M&E.

	1875–1970	1890–1970	1900–1970	1930–1970	1950–1970
Belgium			−0.5 %[a]	−0.8%	−11.7%
France				−4.8%	−4.8%
Germany	−0.6%[b]		−1.6%	−3.4%	−4.0%
Italy	0.9%	0.6%	0.5%	0.3%	2.8%
Netherlands	−7.0%	−7%	−0.5%	−0.5%	−2.7%
Portugal			−3.7%[a]	−3.7%	−2.8%
Spain	−1.0%	−1.0%	−1.0%	−1.3%	−2.7%
Sweden	−1.7%	−2.3%	−2.4%	−2.68%	−0.8%
UK	−2.4%	−2,6%	−2.6%	−2.4%	−3.9%
Argentina	−0.4%	−0.4%	−0.5%	−1.6%	−1.6%
Brazil	1.0%	1.8%	2.0%	3.4%	3.9%
Chile	−1.2%	−0.4%	−0.1%	0.4%	0.9%
Mexico	1.2%	−0.5%	−1.6%	−2.0%	−4.1%
Uruguay	−1.6%	−1.6%	0.8%	0.2%	2.4%

[a]1914–1970.
[b]1880–1970.

Table 5. Energy/capital stock in *M&E* ratio (TJ per thousands *M&E* units).

	1875	1913	1929	1950	1970
Belgium		29.1a	58.4	35.6	31.3
France				53.1	24.7
Germany	44.10	84.75	102.23	50.6	24.6
Italy	5.4	7.6	19.3	7.9	15.4
Netherlands	26.1	25.6	24.5	25.2	17.3
Portugal		265.9	132.1	45.5	28.4
Spain		70.6	41.5	39.1	15.1
Sweden	25.2	39.9	29.2	12.2	11.3
UK	230.2	143.2	84.1	55.5	28.4
Argentina	36.7	40.2	49.6	37.2	29.8
Brazil	10	4.3	4.6	8.8	16.7
Chile	120.5	50.6	31.7	40	43.3
Mexico	4.4	18.9	25.3	24.6	14.9
Uruguay	28.9c	20.5	12.5	7.2	11.4

(*E* /GDP) of the economies. There is a clear difference in the trends though. While most European countries show decreasing Em/Km&*e* ratios in the twentieth century, the Latin American countries exhibit more mixed results.

Germany, the Netherlands, Sweden and Spain show an initial increase in their respective Em/Km&*e* ratios in the end of the nineteenth century. Given that these countries were relatively late industrialisers within Europe whose energy system switched to coal later, this is exactly what we would expect. However, just as the UK, which had made a more complete transition to modern energy carriers much earlier, and Portugal, for which our data start a bit later, they all witnessed a decrease in the energy–capital ratio, and thus signal efficiency improvements, throughout the twentieth century.

Belgium is somewhat more tricky. We see the decreasing Em/Km&*e* we would expect since the late 1920s. From the First World War until the late 1920s, the Em/Km&*e* ratio increased sharply though, however, as Belgium was heavily affected by the war, this explains largely the anomaly. For France, the available capital datalimit our analysis to a too short period to derive any hard conclusions, but the downward trends we do see for the years available seem to be in line with the other European countries in our sample. The only European outlier is Italy.

In Italy, the transition to modern energy sources happened remarkably slowly. The share of traditional energy dropped just below 50% only just before the Second World War, while over the period 1914–1945, the growth rate of modern energy consumption was actually negative (Bartoletto, 2013). This explains the decreasing Em/Km&*e* in the interwar period. After the Second World War, until the oil crisis of 1973, modern energy consumption (of especially oil) in Italy showed an growth rate of 17% per year (Bartoletto, 2013). Given this impressive rate of energy-deepening and the late transition to modern energy sources, the increasing Em/Km&*e* ratio after the Second World War can be explained, but Italy is a marked anomaly within the European countries.

The Latin American countries display very mixed results. Argentina does show signs of efficiency improvements. The very high energy–capital ratio of Chile in the late nineteenth century, on par, as the only country in our sample besides Portugal, with the UK, stands out, but can be explained by the very energy-intensive production of Saltpeter which took place there in the second half of the nineteenth century (Badia-Miró & Ducoing, 2015). Nevertheless around the turn of the century impressive capital-deepening also took hold. During the twentieth century, the Em/Km&*e* ratio barely improved.

For the case of Mexico, we see roughly an inverted U-shape in the way we have also seen it for the late industrialisers in Europe. Mexico only peaked a few years later than the European countries, indicating a later uptake of modern energy carriers. Mexico was also the only Latin American country in our sample where import substitution industrialisation did not take place in the same form than the rest of countries. Although the country was behind, it did develop its own machinery and exhibits comparable efficiency improvements.

The very high energy–capital ratio of Chile in the late nineteenth century, on par, with the UK, stands out, but can be explained by the very energy-intensive production of Saltpeter which took place there in the second half of the nineteenth century. Nevertheless around the turn of the century, impressive capital-deepening took hold. During the twentieth century, the Em/Km&*e* ratio barely improved.

Brazil showed very low Em/Km&*e* ratios throughout most of the twentieth century, but they increased steadily since the First World War, only to accelerate after the Second; its late uptake of modern energy carriers has made the Brazilian case comparable to Italy. Uruguay, finally, appears to demonstrate an inverted U-shape until the 1950s, even though the Em/Km&*e* ratio thus decreased for some decades, this decrease did not continue after the Second World War. As we saw in Table 3, this is mainly the result of a sudden stagnation of the growth of the capital stock.

Overall, we can thus confirm the findings of Kander et al. (2013) for the (Western) European countries, but although decreasing E/K ratios have been the norm in the more developed parts of the world, they ocurred less in the developing region of Latin America. Second, we can also extend the findings by Csereklyei et al. (2016) and see that the divergence between Europe and Latin America is not only a result of the Third Industrial Revolution taking place since the 1970s. It is more structural. This has a number of implications: First, the structural backwardness of Latin America in terms of its energy efficiency hampers its economic development. The lack of efficiency improvements signals lack of innovation and a lack of investment in modern (i.e. more energy efficient) capital that could contribute to economic development. As Latin American countries grew their capital stock largely by importing second hand machinery and equipment from Europe (Tafunell & Ducoing, 2016), opportunities for catch up were also limited because of the constant backwardness in the efficiency of this machinery; as we saw, the only notable exception was Mexico, a country which did not follow a policy of import substitutionindustrialisation and the only country with a 'modern' Em/Km&*e* pattern.

We argue that decreasing Em/Km&*e* ratios are important for economic development, but also signal economic development as they are also indicative of investment in new, more energy efficient, capital goods. When an investment in physical capital is made, i.e. the machine or infrastructure has been put in place, the energy consumption is more or less determined. In such a so-called putty-clay model, which tends to hold for energy consuming capital, richer countries can be expected to have invested more in higher quality, more energy-efficient, capital. Hence, a lower energy–capital ratio is indicative of more economic prosperity, while a decreasing E/K ratio over time is indicative of economic development. Whereas Western European countries managed to keep investing in new and better machinery, Latin America stayed behind and did not succeed in keeping up with the developments in the Western World, and therefore also entered a path of slower growth.

5. Conclusions

In this paper, we compared the long-term trends in energy–capital ratios of nine Western European and five Latin American countries. We found, following up on Kander et al. (2013) and Csereklyei et al. (2016), that the Em/Km&*e* ratios in the Western European countries in our sample, overall, decreased steadily over the course of the twentieth century (Italy being the only exception)[13] Latin American countries show more mixed results, and stayed behind in this development. We covered the period 1875–1970 and argue that the rapid decrease in energy–capital ratios in Europe in the twentieth century, as compared with Latin America, can (in part) explain the economic divergence between the two regions. Decreasing Em/Km&*e* ratios signal investment in modern, more energy efficient, machinery. These investments can foster economic growth and build the bases for structural change and development.

Finally, energy efficiency improvements are crucial for sustainable growth. Kander et al. (2013, pp. 339–341) make clear that capital cannot endlessly substitute for energy as a certain level of energy will always be needed to power machines. Nonetheless, improving efficiency is crucial, not only because output requires less energy, but also because relatively less emissions are produced. Sustainable catching up of underdeveloped and developing regions with the developed world implies opting for an efficient and not detrimental road.

Acknowledgments

We thank Astrid Kander and participants at the Lund University Economic History Seminar, the University of Groningen SOM PhD Conference, El Colegio de México Economic History Seminar, University of Barcelona Economic History Seminar, Public University of Navarra, Economics Department Seminar, the Forum RIDGE in Montevideo and the Economic History Seminar at Umeå University for their valuable feedback on this paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Cristián Ducoing acknowledges the funding by Comisión Nacional de Investigación Científica y Tecnológica (CONICYT), Chile, with the project PAI:82130021 and Jan Wallanders och Tom Hedelius Stiftelse samt Tore Browaldhs Stiftelse 'Engines for sustainability. Horsepower prices, capital substitution and energy transitions in the long run'. Mar Rubio acknowledges the financial support by Ministerio de Educación, Cultura y Deporte Spanish Government, project HAR2017-86086-R.

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[13]Note that, as mentioned before, Kander et al. and Csereklyei et al. used total energy consumption and total capital stock; due to data limitations, we were compelled to restrict our analysis to modern energy consumption and capital stock in machinery and equipment.

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